Extreme Mechanics Letters 29 (2019) 100471

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Design 3D metamaterials with compression-induced-twisting characteristics using shear–compression coupling effects

Xiang Li, Zhenyu Yang *, Zixing Lu *

Institute of Solid Mechanics, School of Aeronautic Science and Engineering, Beihang University (BUAA), Beijing, 100083, China

ARTICLE INFO

Article history:
Received 22 January 2019
Received in revised form 24 March 2019
Accepted 20 April 2019
Available online 25 April 2019

Keywords:
Metamaterials
Compression-induced-twisting
Analytical model
Finite element simulation

ABSTRACT

Metamaterials with compression-induced-twisting (CIT) features shows great potential applications in sensors and actuators. In this paper, a series of 3D metamaterials are developed with the inspiration of the shear–compression coupling effect of the 2D materials, which exhibits twisting behavior when subjected to uniaxial loading. Analytical solutions and numerical simulations are both carried out to demonstrate the possible CIT performance of the proposed 3D metamaterial models, with good agreement obtained. A linear relationship between the 2D shear–compression coupling effect and the twist angle per axial strain of the 3D structures is also deduced. In addition, the twist angle per axial strain can be designed to be infinite. This concept of CIT metamaterials in this paper might shed light on the design and optimization of 3D architectures with multifunctional applications.

1. Introduction

Engineered materials with none occurring properties in natural materials (or called metamaterials) have attracted enormous attention in the past decades for their unprecedented effective properties. Man-made metamaterials are products of human ingenuity, which exhibit lower densities [1], cloaking behaviors [2–4], programmable mechanical properties [5,6] and guiding heat flux as well as tunable sonic frequency [7,8]. Especially, a series of metamaterials typically show unique performance such as negative Poisson's ratio [9–11], negative compressibility [12], and negative stiffness [13], which are opposite to that of the traditional structural materials.

New conceptual metamaterials were designed by combining two different metamaterial properties [14–18]. For example, metamaterial with both negative Poisson's ratio and negative stiffness properties could be achieved simultaneously [15–18]. In addition, the mechanical properties of the materials with negative Poisson's ratio can also be programmable [19]. Recently, a 3D metamaterial with a twist behavior under compression was proposed [20], showing promising future in aerospace engineering, smart actuators and propellers, smart flexible microelectronics as well as biomechanical devices. The obtained twisting property was contributed to the microstructure referred to the chiral structure. Following this work, Wu et al. [21] also proposed an architected cylindrical tube based on a chiral structure, and a linear relation between rotation angle and compression force was obtained. A systematic investigation was conducted by Ma et al. [22] on the architected cylindrical tube. A novel 3D chiral lattice was proposed by Duan et al. and the micropolar theory was adopted to characterize the constitutive behaviors [23]. Moreover, a class of 3D chiral structures was proposed by Fernandez-Corbaton et al. [24]. By using a systematic topology optimization method, Chen et al. [25] found that the topological pattern of the metamaterial with a twist under axial strain is not unique and a twist of the material depends on the size of the material unit cell. Jeon et al. [26] studied the torsional behavior of the carbon nanotube yarns induced by tension. These works mentioned above were focused on the twist properties of the 3D structures, however, the quantitative relationship between the twist angle and axial strain of the metamaterials was still not clear.

In this paper, three different 3D architectures are proposed with considering the shear–compression coupling effect. The first model demonstrates a twisting performance when the structure is subjected to compression in any of the three principal directions. The second model can twist when the structure is under compression in two of the three principal directions. While the third model is a tube-like structure and only shows a twist under compression along the axial of the tube. The twist performances of the materials are highly dependent on the shear–compression coupling effect of the microstructure and the size effect of the structure. Analytical solutions finally are carried out to formulate the twist angle per axial strain of the structures, and numerical

* Corresponding authors.
E-mail addresses: zyyang@buaa.edu.cn (Z. Yang), luzixing@buaa.edu.cn (Z. Lu).

https://doi.org/10.1016/j.eml.2019.100471

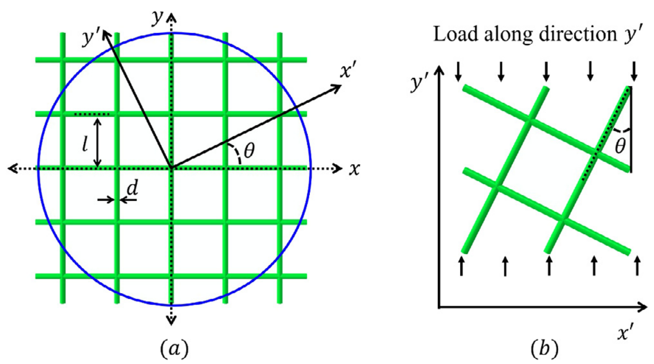

Fig. 1. (a) Geometry of the square lattice and (b) square lattice under an off-axial load with $\theta = 26.6°$.

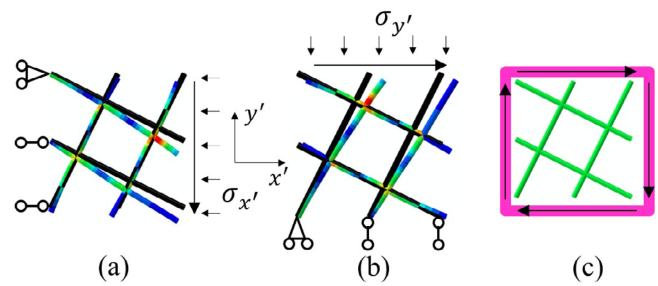

Fig. 2. (a) Deformation of the square lattice under an off-axial load along the direction x', (b) deformation of the square lattice under an off-axial load along the direction y' and (c) deformation mode of the square lattice under off-axial.

simulations are adopted to validate the analytical solutions. It is found that the extreme value of the twist angle per axial strain can be designed to be infinite.

2. Axial–shear coupling effect of the 2D materials

The constitutive relation between strain and stress of a material can be expressed with the compliance tensor **s**,

$$\boldsymbol{\varepsilon} = \mathbf{s}\boldsymbol{\sigma} \tag{1}$$

For 2D materials, the relation can also be written in the matrix form

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{13} & s_{23} & s_{33} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \tag{2}$$

Considering the symmetry of the microstructure of 2D materials, we have

$$s_{13} = s_{23} = 0 \tag{3}$$

which means that when the material is subjected to shear stress, the axial deformation is 0. I.e. the shear and axial deformation of the material are independent, which is identified as a 2D material without shear–compression coupling effect. Regular triangle [27], diamond [28], Kagome [29] and mixed triangular [30] structures et al. are in the family of this structure based on this definition.

Considering the square lattice as shown in Fig. 1, the in-plane length of the ribs of the square honeycomb is l. The cross-section of the ribs is a circle with diameter equals to d. The principal directions are x and y, respectively. While x' and y' are two off-axial directions vertical to each other (see Fig. 1). And θ is the angle between the principal and off-axial directions. Fig. 1b shows a square lattice under an off-axial load with $\theta = 26.6°$. The effective elastic moduli of the square honeycomb on the principal directions are written as

$$E_x = E_y = \frac{\pi d}{4l} E_s \tag{4}$$

$$G_{xy} = \frac{3\pi d^3}{32 l^3} E_s \tag{5}$$

where, E_s is the Young's modulus of the matrix material. The Poisson's ratio of the solid cell wall plays less role in the whole structure. If we do not consider the Poisson's ratio of the solid cell wall, the effective Poisson's ratio of the square honeycomb is 0. Consequently, the compliance tensor **s** on the principal directions are expressed as

$$\mathbf{s} = \begin{bmatrix} \frac{4l}{\pi d E_s} & 0 & 0 \\ 0 & \frac{4l}{\pi d E_s} & 0 \\ 0 & 0 & \frac{32 l^3}{3\pi d^3 E_s} \end{bmatrix} \tag{6}$$

2.1. Shear–compression coupling effect induced by topological asymmetry

With $s_{13} = s_{23} = 0$, and no shear–compression coupling effect can be found when the square lattice is subjected to compression on the principal directions. The compliance tensor **s** is constant for a given material, however, the components of the compliance tensor are dependent on the selected coordinates. As shown in Fig. 2, obvious shear deformation is observed when the square lattice is subjected to off-axial compression, and the symmetry of the structure is broken.

The boundary conditions of the square lattice under off-axial loadings are illustrated in Fig. 2a and b. When the square lattice is compressed in the direction of x', the corresponding displacement of the left side of the structure is constrained. Compared with the left side of the lattice, the opposite side moving down can induce the deformation of shear (Fig. 2a). Similarly, when the lattice is under compression in the direction of y', the displacement of the bottom side of the structure is constrained. In addition, the top of the lattice moves toward the right with respect to the bottom side (Fig. 2b). By combining the two deformations in two principal directions, the deformation mode of the square lattice under the off-axial load is shown in Fig. 2c, the arrowed line presents the deformation direction of the structure when subjected to the load vertical to the arrow direction.

It is obvious that components of the compliance tensor on the off-axial directions s'_{13} and s'_{23} are no longer 0. More details are presented in the discussion part and another deformation mode of the shear–compression coupling effect is analyzed in the following section.

2.2. Shear-compression coupling effect induced by structure symmetry

For the convenience of description, the structure is named as X–S structure in this paper, as shown in Fig. 3c, in which the opposite angles of the square lattice are connected with two inclined cell walls, exhibiting different mechanical properties. The cell walls in green are stiff and the red ones are soft. The Young's moduli of the green and red cell walls are E_s and E'_s, respectively. The geometry of the X–S structure remains to be symmetry with respect to the load directions, while the Young's